Results of Large-Scale Spacecraft Flammability Tests

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The preliminary results for two flights of the Spacecraft Fire Experiment (Saffire), conducted on an orbiting spacecraft, are presented. These experiments directly address the risks associated with our understanding of spacecraft fire behavior at practical length scales and geometries. The result of this lack of experimental data has forced spacecraft designers to base their designs and safety precautions on 1-g understanding of flame spread, fire detection, and suppression. However, low-gravity combustion research has demonstrated substantial differences in flame behavior in low-gravity. Over the past several years, NASA and an international team of investigators have worked to address open issues in spacecraft fire safety. NASA's Spacecraft Fire Safety Demonstration Project was developed with a goal to conduct a series of large-scale experiments in true confined spacecraft environments that represent practical spacecraft fires. The first two flights are complete and examined spread over a large thin sheet of flammable fuel (cotton/fiberglass 41 x 94 cm) and over 9 samples (5 x 30 cm) of various materials (silicone (4), PMMA (2), cotton/fiberglass (2) and Nomex®) that addressed the conditions of NASA STD 6001 Test 1 (material flammability). These experiments were performed on two separate unmanned ISS re-supply spacecraft after they had delivered their cargo and had begun their return journeys to Earth (destructive reentry).

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Preliminary flame spread rates and flammability assessments are presented for the conditions studied with comparison to prior data. A computer modeling effort is underway to complement the experimental effort. In addition, conceptual development has begun for three more flights that will include fire detection and suppression objectives to the program.

I. Introduction

NASA currently relies on a test performed on Earth to rate materials for space use [NASA-STD-6001B]. If a material passes the test then it is assumed that it will be safe in the microgravity environment of space. However, there is a growing body of evidence from reduced-gravity experiments and theoretical predictions that some materials which do not burn on Earth will burn in space in similar conditions, as first suggested in Ref. 1. Understanding the ignition and flame growth of burning materials is central to developing fire safety protocols for space.

An upward-spreading (concurrent-flow) flame on Earth is nearly always more hazardous than a downward-spreading (opposed-flow) flame. However, it is unclear which configuration is more hazardous in reduced gravity. Research shows that the answer may depend on the speed of the oxygen stream,[2] so extrapolating Earth-based test results to space is even further complicated.

Comparing buoyant and purely-forced flows (such as can be realized only in microgravity), there is an intrinsic and substantial difference in the boundary layer structure and the way in which air flows in and around the flame. The simplest way to compare the two situations is to specify a representative flow velocity, and assume that this single value is adequate to characterize the contribution of the flow. For forced flow, the obvious choice is the free-stream velocity. For buoyant flow, there is some judgment about which velocity to use, depending on the aspect being examined, since the flow accelerates over the length of the flame. In some cases, it makes sense to use the buoyant velocity at the base of the flame since this is the stabilization point. In other cases, the relevant buoyant velocity could be based on the overall length scale of the flame. Furthermore, the characteristic buoyant flow velocity may change with time since it depends on the flame size which usually grows in 1-g. It is important to keep these issues in mind when trying to relate 1-g buoyant results to the purely-forced-flow microgravity results.

Although large-scale fire tests on Earth are common, they had never been attempted in a space experiment for obvious reasons of practicality and safety. This is despite the fact that fire is a catastrophic hazard for spaceflight where the crew has very limited or no escape options. The spread and growth of a fire, combined with its interactions with the vehicle cannot be expected to scale linearly based on small-scale test data, and so there remains a substantial gap in our understanding of fire behavior in spacecraft.

Finally, there is evidence that some materials which pass the normal-gravity NASA standard flammability test may yield contrary results in microgravity. But there has not yet been a systematic attempt to compare 1-g standard test results to materials burning in microgravity exposed to comparable flow conditions and igniters.

II. Experiment

The Saffire experiments investigate large-scale fires initiated inside a spacecraft. For safety, they were conducted in Orbital ATK's* Cygnus vehicles, unoccupied spacecraft used to ferry supplies to the International Space Station (ISS).[3] The vehicles launched to the ISS with Saffire stowed onboard. Saffire stayed in the resupply vehicle and remained dormant while the vehicle was berthed with the ISS and its supplies were unloaded. After all supplies had been transferred, the crew carefully stowed trash in the resupply vehicle, leaving adequate free volume to conduct the Saffire experiments. Once the vehicle departed ISS, the Saffire tests were completed and all data was relayed to Earth. Finally, the vehicle was guided for destructive reentry into the Earth's atmosphere.

Fig. 1 depicts the hardware, which enclosed a rectangular flow duct measuring 46 x 51 cm in cross section. Air flowed through the duct uniformly during the tests. In the first flight, a fabric-blend comprising 52 g of cotton and 17 g of fiberglass and measuring 94 cm long by 40.6 cm wide, was mounted on a metal frame in the center of the flow duct. This sample was an order of magnitude larger than anything studied to date, and was of sufficient scale that it consumed 1.5% of the available oxygen in the atmosphere of the vehicle. The non-combustible matrix of fiberglass remained after the flame spread to prevent the fabric from cracking and curling which would destroy the symmetry of the flame and complicate the modeling of the system. Ignition was caused by a resistively-heated hot wire (29-gage

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* Commercial entities, equipment, or materials may be identified in this document in order to describe the experimental procedure or facility adequately. Such identification is not intended to imply recommendation or endorsement by the National Aeronautics and Space Administration.

Kanthal®, 0.286 mm, 3.85 A) which was woven across the sample in a saw-tooth pattern. The igniter was powered for 8 s at a constant power of 182 W.

The initial flight experiment (Saffire-I) was performed at a flow speed of 20 cm/s and the initial oxygen concentration as reported by the ISS at the time the vehicle departed was 21.7% O_2. The original intention was to conduct only the first test, and the second test was a contingency in case the igniter failed, the air flow shut off, or the initial flame extinguished prematurely. Everything performed nominally for the first test which was allotted 420 s before the air flow turned off. After 210 s, the flow was re-established and the contingency test was initiated. Since telemetry was unavailable during operations, the software was written to perform both tests dutifully without regard for whether or not there actually was a flame. As it turned out, the flame in the first test was slower than anticipated, burning only about 90% of the fuel and leaving 10% unburned (based on the uncharred area). Therefore, the second test yielded meaningful data, although it was relatively brief since only a fraction of the fuel remained.

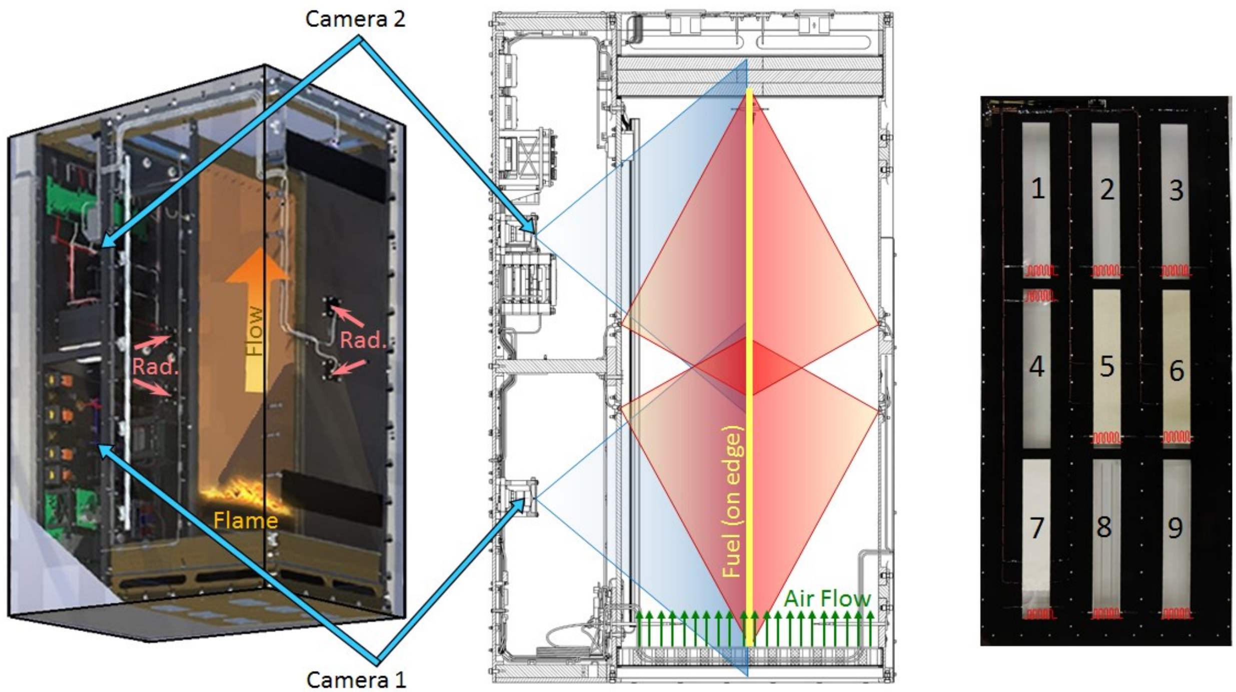

Figure 1. The Saffire Flow Duct. *The Saffire-I large sample configuration is shown on the left. Two cameras and four radiometers are indicated. In the center drawing, the camera and radiometer fields of view are shown by the cones, shaded blue and red, respectively. The right panel shows the Saffire-II sample card with the nine samples, and ignition locations are indicated in red.*

In the second flight experiment (Saffire-II), the initial oxygen concentration as reported by the ISS at the time the vehicle departed was 22.1% O_2, slightly higher than the first flight (21.7%). Nine samples were mounted on the sample card, as shown in the right panel of Fig. 1, and each measured 5 cm wide by 30 cm long. The average air flow speed through the duct was 20 cm/s for all tests except for Sample 5 which was run at 25 cm/s. All samples except for Sample 4 were ignited at their most upstream location, yielding a concurrent-flow configuration. The ignition energy and time for samples 1 through 7 were chosen to mimic the NASA 6001 Test 1 ignition, 736 J applied uniformly for 9.2 s.[4] The igniters consisted of resistively-heated hot wires (29-gage Kanthal®, 0.286 mm, 3.85 A) which were shaped in the form of a sinusoid having eight peaks spanning the 5-cm fuel width. Peaks were alternated on either side of the fuel edge to create good contact with the fuel surface. The amplitude of the sinusoid shape was 1.3 cm, and the total (straightened) length was about 25 cm. Samples 8 and 9 had slightly more powerful igniters (97 W instead of 80 W) and were left on longer (30 s instead of 9.2 s) to assure ignition of these thick fuels. Total energy applied was 2900 J. For these thick PMMA samples, the igniter was wound into a tight coil with a diameter of around 0.5 cm and then threaded through 18 closely-spaced holes on the tapered end of the fuel across the 5-cm width.

A variety of materials and geometries were examined. Samples 1 to 4 were sheets of silicone measuring 0.27, 0.61, 1.03, and 0.37 mm thick, respectively. Samples 5 and 6 were cotton-fiberglass fabric identical to that used in the first flight and described above. Sample 7 was a composite sample, the first 5 cm of which was a thin (0.8 mm) sheet of PMMA and the remainder Nomex® fabric (HT 90-40). Samples 8 and 9 were polymethyl methacrylate

(PMMA) slabs with a nominal thickness of 1 cm. Sample 8 had some surface features, including a groove down the center (in the flow direction) on both sides of the sample, while the surfaces on Sample 9 were flat.

For both experiments, two cameras imaged one side of the burning sample, with each spanning just over half of the sample. The flow duct was darkened in order to facilitate flame imaging, but the fuel sample was illuminated periodically so that the char front could be seen as the fuel burned. Four radiometers measured front and back-side radiation coming from the flame and fuel surface. Each radiometer covered just over half of the sample, with two on each side to provide an indication of symmetry between the front and back halves of the flame. Thermocouples were arrayed to provide temperature measurements at key location on and near the fuel and throughout the flow duct. Oxygen concentration, carbon dioxide, and pressure were also recorded just upstream of the fuel in the flow duct.

III. Results and Discussion

For the two flight experiments, a total of 11 ignitions were attempted for the variety of fuel samples. The results are grouped by material type.

A. Silicone Sheets (Flight 2, Tests 1 to 4)

The first three silicone samples had thicknesses 0.27, 0.61, and 1.03 mm, respectively. These samples were chosen based on the results from ground tests.[5] In upward-burning, normal-gravity tests, the 0.27-mm thick samples were almost always completely consumed (of the six tests, only two did not burn the entire sample but both of these burned at least 20 cm of the available 30-cm length.) The 0.61-mm samples burned on average 8 cm of the available 30 cm before extinguishing, and the 1.03-mm samples would not burn at all. In normal gravity, these three thicknesses spanned the flammability limits for this material from significant burn, to partial burn, to no burn. The corresponding behavior in microgravity was sought, specifically, how much of the available fuel would be burned, and whether microgravity would prove more or less favorable to flame spread. The average concurrent-flow air speed in the duct was 20 cm/s for all three tests. The ignition system was identical to what was used in normal gravity.

Results were convincing although rather anticlimactic. While the igniter was powered, a gas phase flame appeared in its vicinity, however for none of the sample did the flame persist nor spread away from the igniter. When the igniter was powered off, a tiny gas phase flame remained but did not spread and quickly extinguished. The igniters all appeared to function normally and the samples were clearly damaged in the vicinities of the igniters.

It was surprising that not even the thin sample could permit any flame spread, given that it was entirely consumed in normal gravity. Previous experience with cellulosic fuels (paper and fabric) and even PMMA suggested that if a flame could persist in upward 1-g tests then it would also burn in microgravity at a moderate flow speed which was less than that typical in buoyant flow.

The behavior of silicone in microgravity is perplexing. We know that silicone produces fine silica powder as it burns, which could be deposited on the fuel and impede pyrolysis. The relatively-higher buoyant flow speeds could sweep out the silica at a high enough rate so that it does not hamper combustion. Also, the silicone fuel becomes quite irregular as it burns, cracking and flaking off in complex ways. The surface reaction details and geometrical effects could significantly impact the observed results. In fact, the buoyant flow might aid the cracking and flaking processes which in turn could promote combustion as fresh fuel is exposed.

The fourth silicone test was an opposed-flow burn of a 0.37-mm thick sample. The downstream-end of the sample was ignited, comparable to a downward burn in normal gravity where the flame spreads "opposed to" the direction of the buoyant flow. Again, this sample was chosen based on the normal gravity tests,[5] where the sample was completely consumed. (In these tests, the sample was either completely consumed or did not spread at all.) This thickness was a boundary point in that the next higher sample thickness tested (0.61 mm) would not burn downward on Earth. In microgravity, the expectation was that the sample would spread, and the difference in the flame spread rate was sought. As with the previous silicone samples, however, a tiny flame remained after ignition but it quickly extinguished. Potential reasons for this result are similar to the ones given above for the concurrent-flow tests.

It would be interesting to repeat these tests in microgravity but at a much higher flow speed of around 60 to 80 cm/s, which is more typical of the level in 1-g. More work is needed to understand the differences between the normal gravity and microgravity flammability of silicone. The one clear observation is that microgravity can still yield unexpected outcomes.

B. Cotton-Fiberglass Fabric (Flight 1, Test 1 and 2; Flight 2, Tests 5 and 6)

In the first flight experiment, the 40.6-cm-wide sample was burned first in the concurrent-flow mode and then in opposed-flow. For the concurrent-flow test, the flame was ignited across the upstream-end of the sample. At ignition, the flame was mostly bright and relatively vigorous but it soon developed a blue base and a pattern of orange-yellow radiation coming from incandescent soot. At first, the flame length and brightness varied periodically at about 1.4 Hz before finally becoming stable at about 90 s into the test. Fig. 2 shows the image sequence for one cycle of the fluctuation at about 24 s after the igniter turns off. The reason for the fluctuation is unclear. It may be due to a flow oscillation which is present even in the cold flow, or it may be the result of the flame interacting with the flow field in the first part of the flow duct. After the flame had passed, exothermic surface smolder spots burning some of the leftover fuel were visible. The flame burned the entire allotted test time of about 7 min. at which point the air flow was shut off and the flame immediately extinguished.

The flame base was reasonably flat at first but developed into a non-uniform shape. This shape slowly became more exaggerated as time progressed, as two broad portions of the flame which had moved ahead tended to move even further ahead. At the end of the test, the shape of the flame deviated from flatness by about +/- 5 cm over the 40.6-cm width.

As mentioned above in the description of the experiment, there was a small but sufficient amount of fuel remaining after the concurrent-flow test to permit a second burn, this time in the opposed-flow geometry. Only about 10% of the fuel remained after the concurrent test, but that was enough to make conclusions about the opposed-flow flame spread and development. In this case, ignition was achieved at the top of the sample and the flame spread downward into the flow. The flame quickly reached a steady size and spread rate. However, there were portions of the downstream flame which exhibited shifting patterns of soot indicating that there may have been some flow fluctuations.

The flame speed and size were measured from the video. The flame and pyrolysis position traces for the concurrent-flow and opposed-flow tests are shown in Fig. 3, revealing that spread rate was steady for most of the tests. For the concurrent flame, after a transient that drives an overshoot in the pyrolysis length,[†] that length reached a plateau value of around 40 mm, while the opposed-flow pyrolysis length was a bit shorter at 24 mm. The average concurrent-flow flame spread rate was 1.8 mm/s which corresponds to a theoretical heat release rate of 1.5 kW (assuming perfect fuel conversion). The opposed-flow flame average spread rate was 30% slower at 1.3 mm/s (1.1 kW). At the end of the concurrent-flow test, the spread rate is beginning to increase, but this may be due to local flow acceleration effects near the end section of the duct.

Part of the contribution to the initial overshoot in the pyrolysis length may be attributed to flame fluctuation discussed above. The fluctuations are most significant for the first minute then begin to die away. This coincides with the peak in the length. Basically, the flame pulses forward causing

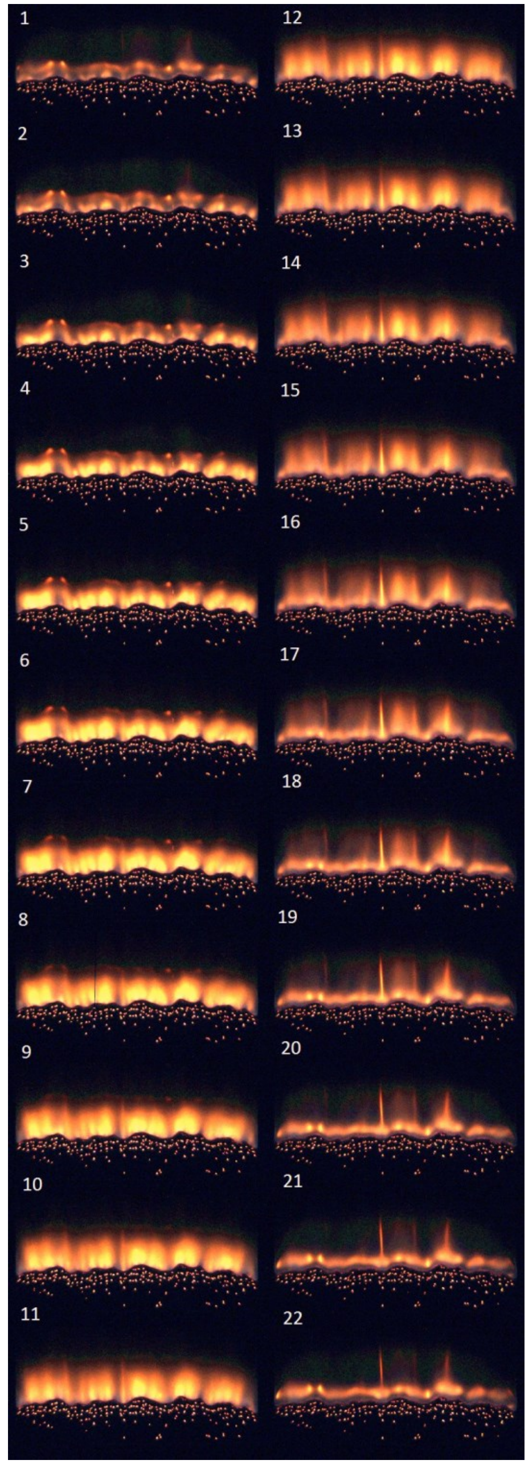

Figure 2. Flame Fluctuations. *Microgravity image sequence (30 Hz) of 40.6-cm-wide fabric burning in air at 20 cm/s concurrent-flow speed. Images start 24 s after the igniter is turned off.*

[†] Here, the pyrolysis length is defined as the distance from the base of the flame (which coincides with the fuel burnout point) to the point on the fuel which is first visible blackened. If the gas-phase flame is steady, the pyrolysis length generally coincides with the flame length.

the fuel to pyrolyze (blacken) at a higher rate than if the flame was stable at its average length. There may be other reasons contributing to the length overshoot related to the ignition transient and the nearby initiation point of the boundary layer on the fuel sample holder.

In the concurrent-flow tests, the sample was instrumented with six thermocouples arrayed in two groups approximately 32 and 62 cm from the igniter. Each group comprised three thermocouples near the centerline of the sample: one surface-mounted and two in the gas-phase. When plotted on top of each other, the surface temperature traces are virtually indistinguishable, another verification that the flame had indeed reached a steady condition.

In the second flight experiment, Samples 4 and 5 were of the same fabric material but measured only 5 cm in width by 30 cm in length. They were mounted centrally on the 9-sample fuel card (see right panel of Fig. 1). Both were burned in the concurrent-flow configuration with Sample 5 at an air flow speed of 20 cm/s and Sample 6 at 25 cm/s. The flames for both tests were very stable in appearance and spread at steady rate, except for a very brief ignition transient. The flame bases were flat and mostly horizontal across the sample width, and the flame tips were dome-shaped. Towards the end of the burn for Sample 6, the flame base began to tilt slightly with respect to horizontal but remained straight, finally ending at an angle of approximately 13.5 deg. which was maintained for the last 35 s of the burn. For Sample 6, the flame was slightly longer and spread at a higher rate compared to Sample 5.

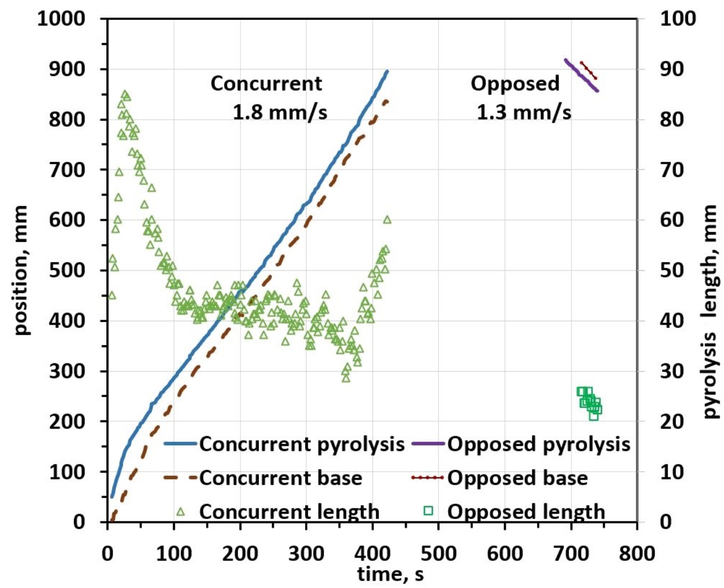

Figure 3. Sample Measurements. *Flame base, pyrolysis tip, and pyrolysis length for concurrent and opposed-flow tests. Fuel was a 40.6-cm-wide cotton-fiberglass fabric. Air flow speed was 20 cm/s.*

In Fig. 4, the concurrent and opposed flame spread rates for the large samples along with the spread rates of the two smaller samples are plotted on the same graph with previous results obtained in microgravity.[6] The majority of points were obtained in the earlier tests with significantly smaller sample sizes measuring either 2 x 10 cm or 1 x 10 cm. Flow speed is indicated on the x-axis, with points plotted to the left of the origin representing concurrent-flow tests and points plotted to the right, opposed-flow. For concurrent-flow flames, the spread rate increases linearly with flow speed while for opposed-flow flames the spread rate peaks at a moderate flow speed (20 cm/s) before dropping off as flow increases.

Comparing the two large-scale burns in this work, the concurrent-flow spread rate is markedly faster than the opposed-flow. However, there is some experimental and theoretical evidence which predicts that the faster mode is determined by flow speed.[2,7,8] At low speeds, the opposed-flow spread is faster while at higher speeds the concurrent spread is faster. There is a crossover point where the two rates are equal. It appears that the 20 cm/s flow condition for the Saffire experiment is above the crossover point where concurrent spread is faster compared to opposed-flow.

The flame spread rate for the 5-cm-wide sample is marginally faster compared to the spread rate for the 40.6-cm-wide sample for the same flow speed of 20 cm/s. This may be due to the slightly higher starting oxygen percentage (22.1% vs. 21.7%). However, the 5-cm-wide sample might have spread faster because of larger side entrainment effects compared to the wide sample.

The Saffire concurrent-flow flame spread more slowly compared to the prior microgravity tests burning smaller-width samples of the same fuel in similar conditions.[6] These earlier tests were conducted in a more confined flow duct where the thermal expansion of the hot combustion gases caused the free stream to accelerate, forcing the flame closer to the fuel sample and leading to a higher spread rate. An important consideration for spacecraft fires is revealed, namely that a flame burning in a larger, more open volume will be quite different compared to a flame burning in a more confined volume even if fuel and flow parameters are otherwise comparable. For example, a ventilated flame located behind a panel or between components in microgravity may be more hazardous than if it was in a bigger volume.[9] Flow confinement may not change whether or not a flame propagates. However, a confined flame may spread faster,

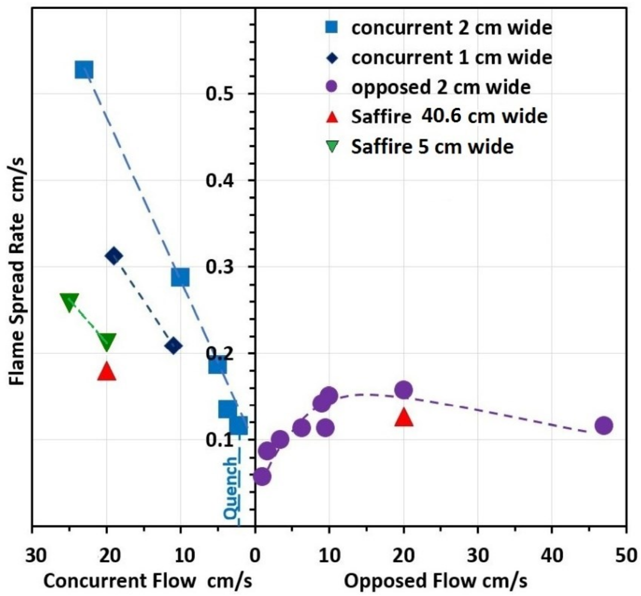

Figure 4. Spread Rate Summary. *Cotton/ fiberglass fabric burning in microgravity. Concurrent flames are shown to the left of the origin, and opposed to the right.*

yielding higher rates of heat release, combustion product buildup, and vehicle temperature and pressure rise. This is an important consideration for evaluating spacecraft fire scenarios.

For all tests, the pyrolysis and flame lengths reached a nearly steady value. Even for non-thin samples, a theoretical model predicts a limiting length in microgravity.[10] After growing to the limiting length, the flame becomes stationary until the flame base moves (i.e. sample burnout). This has recently been verified in a space experiment which burned thick plastic rods of fuel in low-speed concurrent flow.[11] Gas phase diffusion flames burning over a porous metal plate in microgravity at a constant fuel flow rate also exhibited a limiting flame length due to quenching at the flame trailing edge, attributed to soot radiation.[12] On the other hand in earlier experiments, 1-g upward spread over a tall, thick, sample yielded a continuously growing flame. The investigators reasoned that this behavior was enabled by increasing soot radiation of the larger flame,[13] highlighting here the ambiguous role that soot may play depending on the convective environment.

C. Composite PMMA-Nomex® (Flight 2, Test 7)

The purpose of this test was to see how a material rated "safe" by the NASA 6001 Test 1 standard test reacted during extended exposure to a flame in microgravity. The material is a meta-aramid fabric commonly used on the ISS called Nomex® HT90-40. On Earth, it will only burn if the oxygen concentration is increased to around 24 to 25%.

This composite sample measured 30 cm long by 5 cm wide. A thin sheet of PMMA (0.8 mm thick) comprised the first 5 cm of the length. Then there was an overlap area about 7 mm long where the PMMA and the fabric were in intimate physical contact. The remainder of the sample was fabric.

The flame was produced by igniting the thin sheet of PMMA. A robust flame rapidly developed and spread across the plastic reaching a maximum length of around 10 cm. The flame was bright orange-yellow and quite unsteady, in appearance, likely due to the formation and ejection of gas bubbles in the plastic as it pyrolyzed. It took about 2 min. for the PMMA to be consumed, all the while the flame plume was extending over and heating the base of the Nomex® fabric. The average flame power from the PMMA (assuming complete conversion of the fuel) was 460 $\pm$ 50 W. Despite this significant heating load, the fabric was not ignited. The first 1-cm of the fabric was significantly damaged, the first 5-cm was completely blackened, and the remainder had a black streak down its center. However, some of this discoloration may have been caused by deposition of soot from the PMMA flame on the fabric, and not necessarily pyrolysis of the fabric itself.

D. Thick PMMA (Flight 2, Tests 8 and 9)

Samples 8 and 9 were 30-cm-long, 1-cm-thick slabs of PMMA, with cross sections as shown in Fig. 5. Ignition occurred on their upstream ends, which were tapered down to facilitate ignition. The samples were 1 cm in thickness, except for the middle 1.8-cm-wide portion of Sample 8 which was only 0.4 cm thick. For Sample 8, the effect of edge shape on flame spread was of interest and the side edges were exposed to air. Sample 9 was a simple flat slab, and its edges were covered with a thin metal strip to inhibit combustion there.

The 97 W igniter was powered for 30 s and resulted in ignition for both cases. The flame was ignited within two seconds after the igniter was powered, and it quickly grew into a robust, orange-yellow, fluctuating flame. But the flame only maintained its appearance for the 30 s during which the igniter was on, and as soon as the igniter was shut off the flame became a small, dim, blue flame just barely burning the sample. After about 20 s for Sample 8, and 75 s for Sample 9, the flame began to develop visibly incandescent soot. (The flame burning Sample 8 was quicker to develop because the fuel had a relatively thin portion.) Then, the flames strengthened significantly and became bright orange-yellow. As with the thin PMMA in the composite Sample 7, there was significant flame fluctuation as gas bubbles formed in the fuel due to pyrolysis were rapidly released. The flames extended about 5 cm in length on average and fluctuations caused by ejecting bubbles reaching as much as 10 cm. Samples 8 and 9 were allowed to burn for 10 and 15 min., respectively. The flame took about 5 s to become extinguished once the air flow was turned off. In both cases, the flame significantly consumed or damaged about the first 5 cm of fuel length, and the next 5 cm had only moderate to little damage. The thin portion of Sample 8 had a bit more damage, as expected.

The digital images of the burned samples provided a rough estimate of how much fuel was consumed. For Sample 8, it was estimated that 12 $\pm$ 2 g of PMMA was consumed. Based on the radiometer output, the burning event lasted 500 s. (The initial portion right after ignition when the flame was small and blue was ignored). The average fuel burning rate was thus 24 $\pm$ 4 mg/s. Assuming complete combustion of this fuel yields a flame power of 600 $\pm$ 100 W.

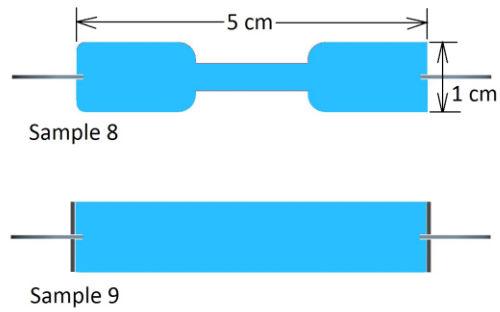

Figure 5. Thick Samples. *The cross sections of PMMA Samples 8 and 9 are shown. Both are nominally 1 cm thick, but the middle 1.8-cm-wide portion of Sample 8 is only 0.4 cm thick.*

The tests of Samples 8 and 9 are described in more detail elsewhere.[14]

IV. Summary and Conclusions

In two separate flight experiments, unmanned ISS resupply vehicles were used to conduct burning tests prior to their destructive reentry into the atmosphere. For the first time, a series of large-scale fires were intentionally set inside a spacecraft while in orbit. In the first experiment, a large fuel sample consisting of a cotton-based fabric sheet was burned in two separate tests. In addition, two smaller samples of the same material were burned in the second spaceflight experiment. The results revealed that a steady flame could be achieved even for a wide sample burning in concurrent-flow. The flames spread more slowly than prior tests in smaller ducts. This behavior of the flame demonstrated the importance of confined spaces for determining the flame spread rate, rate of heat release, and rate of production of smoke and gaseous combustion products. All of these parameters impact how rapidly the cabin atmosphere degrades during a spacecraft fire and how long the crew has to respond.

Silicone samples of different thicknesses were burned for comparison to Earth-based results. It was surprising that for none of the samples could spreading flames be achieved. The samples which burned on Earth could not be burned in microgravity for any of the tested configurations. This behavior may be explained by the fact that silicone produces fine silica powder as it burns, which could inhibit flame spread. Complex burning behavior (cracking, flaking, etc.) may be different in normal and microgravity and so may influence flammability differences in the two environments.

An attempt was made to ignite a Nomex® fabric which has a “safe” rating by exposing it to a flame for an extended period of time in microgravity. Despite some damage which occurred, the fabric could not be ignited. Current fire safety practices for spacecraft rely on rating materials based on 1-g tests and these results suggest that underlying assumptions need to be modified to account for the observed burning behaviors.

Finally, observations about the burning of two separate thick PMMA samples are made. The flames took a relatively long time to develop but were still growing as the test was ended. An estimate of the burning rate was made.

There are plans for the Saffire project to continue with additional flight experiments examining the effects of enhanced oxygen at reduced pressure. The results of this series of large-scale spacecraft fire safety tests will increase our knowledge of how a fire spreads in a large enclosure, and what effects the fire has on the spacecraft atmosphere. This understanding will influence vehicle design and materials screening, ultimately increasing the safety of the crew.

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